

SUMMARY OF RESEARCH

*Origins and Dynamics of Interplanetary Dust Particles*

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## Research Achievements

The contribution of asteroidal dust to the zodiacal cloud has previously been discussed in terms of a collisional cascade process, first described by Dohnanyi (1969), whereby dust is produced by the grinding down of large objects into small particles. In this scenario, the solar system dust bands (discovered by IRAS in 1983; Low et al., 1984) result from the gradual collisional comminution of entire asteroid families, with the prominent “ten-degree” dust band and the near-ecliptic dust bands being produced by the classical Hirayama (1918) asteroid families: Eos, and Koronis and Themis, respectively (Dermott et al., 1984).

However, not all of the dust bands have been unequivocally related to a particular asteroid family source, and neither do all of the most populous families produce a discernible dust band, as might be expected (Reach et al., 1997; Sykes, 1990). There also remain some outstanding problems with linking the original IRAS dust bands to the prominent Hirayama asteroid families. In particular, detailed modeling of the “ten-degree” band has revealed a significant discrepancy between the  $9.35^\circ$  proper inclination of the dust particles required to model the band and the  $10.08^\circ$  mean proper inclination of the Eos asteroid family, its putative source (Grogan et al., 2001).

An alternative theory has proposed that the dust bands result from the catastrophic collisional disruption of individual asteroids, not necessarily family members, in the main-belt (Sykes and Greenberg, 1986). Such collisions could result in the formation of new asteroid families and we note the exciting recent discovery of several young asteroid clusters,  $< 10$  Myr old, in the main belt by Nesvorný et al. (2002, 2003). Moreover, there is now growing evidence that many asteroids are not coherent, solid bodies but are instead highly fractured, highly porous, and only loosely bound by gravity (see the review by Richardson et al., 2002). Dust may also be generated by impact processes in the regoliths of such “rubble piles” (Dermott et al., 2002a) and so the contribution of asteroidal dust to the zodiacal cloud could be determined by a quite different mechanism to the collisional cascade process, with only a few collisionally-disrupted rubble piles providing the majority of asteroidal dust in the solar system at any particular epoch (Dermott et al., 2002b).

The likely prevalence of rubble-pile asteroids combined with the recent discovery of several young asteroid clusters in the main belt has led us to focus our research on investigating the possibility that these recent asteroid break-ups are the dominant source of the IRAS solar system dust bands and the major source of interplanetary dust particles (IDPs) collected on Earth (Dermott et al., 2002b). The product of one of these recent collisional disruptions, the Veritas family, which is estimated to have formed a mere 8.3 Myr ago (Nesvorný et al., 2003), has proven to be of particular interest because it has a mean proper inclination of  $9.25^\circ$ , thereby indicating it as the probable source for the “ten-degree” dust band (Dermott et al., 2002b). We also examined the possibility that the Karin cluster, a component of the Koronis family that has been dated as 5.8 Myr old (Nesvorný et al., 2002), is the dominant source of the near-ecliptic dust band (Dermott et al., 2002b), with a smaller contribution from the roughly billion-year-old Themis asteroid family.

In addition to concentrating our research on these newly discovered young asteroid clusters, another important motivation for the work undertaken through the support of this grant has been a growing appreciation of the significance of large particles (between  $\sim 10^2 \mu\text{m}$  and  $\sim 10^3 \mu\text{m}$  in diameter) to understanding the origin, structure, and evolution of the zodiacal cloud. Recent theoretical results obtained by this research group (Grogan et al., 2001; Wyatt et al., 1999), backed up by observational evidence (Grün et al., 1985; Love and Brownlee, 1993), have indicated the important contribution of these large particles to the interplanetary dust complex and the need to incorporate realistic size-frequency distributions of particles into models of the zodiacal cloud.

Our unique approach to building detailed models of the zodiacal cloud has been to utilize the results from numerical simulations of the dynamical behavior of its constituent dust particles under the effects of radiation pressure, Poynting-Robertson (P-R) drag, solar wind drag, and gravitational forces. These dynamical models are then compared with observational data and refined. However, due to computational constraints, our previous models of the zodiacal cloud were limited to considering small particles, generally less than  $100 \mu\text{m}$  in diameter (for example, Grogan et al., 2001), that spiral rapidly into the Sun under the effect of P-R drag (Wyatt and Whipple, 1950). Larger particles have correspondingly longer dynamical (i.e., P-R drag) lifetimes and hence require longer integration times. For this reason, any comprehensive numerical investigation of the orbital evolution of large particles in the zodiacal cloud would have been computationally prohibitive using traditional techniques. To achieve our goal has therefore required the application of a powerful new  $N$ -body code developed specially for this purpose (Kehoe et al., 2003) that, when allied with moderate computing resources, has allowed the necessary numerical simulations to be performed within a reasonable time frame.

During the tenure of this award, we have successfully investigated the orbital evolution of numerous waves of dust particles covering a wide spectrum of sizes, from  $10 \mu\text{m}$  up to  $1,000 \mu\text{m}$  in diameter, for each of the asteroidal sources discussed above, and up to  $10,000 \mu\text{m}$  in diameter in the case of the Veritas family. In doing so, we have gained valuable insights into the qualitatively different dynamical behavior exhibited by particles at the large-end of this spectrum, as compared to the small particles ( $< 100 \mu\text{m}$  diameter) that we were limited to investigating previously. And importantly, in the case of particles from the relatively young Veritas family and Karin cluster, we have now computed the orbital history of particles that are large enough to have dynamical lifetimes comparable to the ages of the disruption events

that produced them.

In addition, we note that dust particles in the inner solar system with diameters of  $\sim 500 \mu\text{m}$ , or greater, have P-R drag lifetimes comparable to, or greater than, the timescale for the particle to be destroyed by inter-particle collisions (Wyatt et al., 1999), whereas the P-R drag lifetimes of particles much smaller than this are too short for them to be significantly affected by such collisions. The requirement to investigate the evolution of large dust particles therefore means that, in addition to the previously modeled effects of radiation pressure, P-R drag, solar wind drag, and planetary perturbations, the effects of stochastic size changes due to particle fragmentation have also had to be incorporated into our numerical simulations of their orbital evolution. A fundamental goal of the research sponsored by this award has therefore been to study the combined dynamical and collisional behavior of these large particles. We have achieved this by employing a semi-analytic technique that combines the results of secular perturbation theory with numerical integrations using the  $N$ -body code discussed above.

The scale of the numerical simulations required for this investigation is truly enormous even with the use of the bespoke  $N$ -body code (Kehoe et al., 2003). To date we have performed over 2,500 individual simulations using this code and generated over 100 Gb of data. These simulations, which are still ongoing, have so far required a cumulative total of over 18 years of CPU time to complete, running on the departmental network consisting of around 50, mainly Pentium, processors. The results from these dynamical simulations have shown that:

1. The dispersion in both the proper inclination and proper eccentricity distributions of a single-sized wave of dust particles increases with increasing particle size and with decreasing semimajor axis due to the effect of passage through mean-motion and secular resonances.
2. The forced elements defining the plane of symmetry of a single-sized distribution of dust particles tend asymptotically towards the “zero-drag” limit as particle size increases. The “zero-drag” limit is given by the secular perturbation solution, which closely follows the orbital elements of Jupiter in the outer main belt.
3. The inner edge to the dust bands at  $\sim 2$  AU results from the significant effect of the  $\nu_6$  and the  $\nu_{16}$  secular resonances on particle orbits that disperses the dust band signal to the extent that it merges naturally into the flux from the background zodiacal cloud.
4. The effect of inter-particle collisions introduces an additional dispersion in the distribution of the forced elements of the particles as a result of the variation of Jupiter’s orbital elements, and the “zero-drag” secular perturbation solution, over the course of a secular cycle.

These new results provide a more accurate description of the orbital evolution of a realistic size distribution of zodiacal cloud particles and are discussed in more detail by Dermott et al. (2001; 2002a), Kehoe et al. (2002a; 2002b), and in a forthcoming paper by Kehoe et al. (2005).

The results from these dynamical simulations are now being employed to build detailed models of the solar system dust bands. Due to the effect of collisions, the size-frequency

distribution of particles in the zodiacal cloud changes with semimajor axis. We mimic this effect by building multiple individual models for each source of particles that have discrete semimajor-axis ranges and independent size-frequency distributions. These separate “slices” of the zodiacal cloud are then combined, using a weighting function to account for the change in the cross-sectional area of particles as a function of semimajor axis, to create a final model. This model demonstrates that the young Veritas family and Karin cluster are indeed the likely sources of the “ten-degree” and near-ecliptic dust bands respectively, with the Themis asteroid family probably providing an additional small contribution to the near-ecliptic band. This model is the most sophisticated model of the dust bands that has been produced to date and its accuracy in reproducing the shape and amplitude of the dust bands observed by IRAS is very encouraging. As discussed below, preliminary results from this work have already been published and presented at meetings, and a full discussion of the latest results obtained through this research is now being prepared for publication (Kehoe et al., 2005).

The results discussed above are just some of the highlights of the important research carried out through the support of this grant. It is worth noting here that while a better understanding of the origins and structure of the solar system dust bands is intrinsically valuable, its merit also lies in the fact that the dust bands represent the “tip of the iceberg” of the total asteroidal contribution to the zodiacal cloud and are therefore also a key element in determining the provenance of the cloud and its global structure.

We have shown that the dust bands that we currently observe are probably the result of the recent collisional disruption of two relatively small rubble piles: the Veritas and Karin precursor bodies with diameters of about 140 km and 27 km, respectively (Nesvorný et al., 2003). This result suggests the intriguing possibility that the dust particles accreted by the Earth are also dominated by particles from these same two sources. Much larger rubble piles, for example the precursor bodies of the Eos and Themis asteroid families that are estimated to have been 218 km and 369 km in diameter respectively (Tanga et al., 1999), have clearly been disrupted in the past. The disruption of such a large rubble pile could produce a wave of dust of high optical depth that would flow towards the Sun and engulf the Earth resulting in a much higher accretion rate of particles with potentially drastic consequences for Earth’s climate (Dermott et al., 2002a). The quantity of dust liberated by such an event is still unclear, however, evidence of these events in the past may well be contained in the Earth’s sedimentary record (see the reviews by Farley, 2001; and by Peucker-Ehrenbrink, 2001). We aim to determine the geologic signature of such events through a better understanding of the dynamical and collisional evolution of the wave of dust particles released by the catastrophic disruption of a large rubble pile.

It follows, that debris disks around other stars may temporarily flare into visibility after the collisional destruction of a planetesimal. In fact, a recent collaboration with colleagues on the interpretation of new high-resolution thermal infrared observations of the debris disk around  $\beta$  Pictoris has resulted in the publication of an article arguing that the structure evident in these images could result from the recent catastrophic disruption of a large planetesimal in the disk (Telesco et al., 2005; see also Kehoe et al., 2004). Research in the areas discussed above will now be continued through the support of a successor award.

## Publications and Presentations

As a result of support through this proposal, we have published 1 book chapter, 3 articles in refereed journals (plus 1 in preparation), and a total of 14 conference papers either in proceedings or as abstracts.

### Book Chapters

Dermott S. F., Durda D. D., Grogan K., and Kehoe T. J. J. (2002a) Asteroidal dust. In *Asteroids III* (W. F. Bottke Jr., A. Cellino, P. Paolicchi, and R. P. Binzel, eds.), pp. 423–442. Univ. Arizona Press, Tucson.

### Journal Articles

Kehoe T. J. J., Murray C. D., and Porco C. C. (2003) A dissipative mapping technique for the  $N$ -body problem incorporating radiation pressure, Poynting-Robertson drag, and solar wind drag. *Astron. J.*, 126, 3108–3121.

Kehoe T. J. J., Dermott S. F., and Mahoney-Hopping L. M. (2005) Dynamical evolution of asteroidal dust particles and the origin of the solar system dust bands. In preparation.

Holmes E. K., Dermott S. F., Gustafson B. Å. S., and Grogan K. (2003) Resonant structure in the Kuiper disk: an asymmetric plutino disk. *Astrophys. J.*, 597, 1211–1236.

Telesco C. M., Fisher R. S., Wyatt M. C., Dermott S. F., Kehoe T. J. J., Novotny S., Mariñas N., Radomski J. T., Packham C., De Buizer J., Hayward T. L. (2005) Mid-infrared images of  $\beta$  Pictoris and the possible role of planetesimal collisions in the central disk. *Nature*, 433, 133–136.

### Conference Papers

Dermott S. F., Kehoe T. J. J., Durda D. D., Grogan K., and Nesvorný D. (2002b) Recent rubble-pile origin of asteroidal solar system dust bands and asteroidal interplanetary dust particles. In *Asteroids, Comets, and Meteors 2002*, ESA SP-500 (B. Warmbein, ed.), pp. 319–322. ESA Publications Division, Noordwijk.

Dermott S. F., Kehoe T. J. J., and Mahoney-Hopping L. M. (2003) Origins of asteroidal interplanetary dust particles (abstract # 07532). *Geophys. Res. Abs.*, 5.

Dermott S. F. and Kehoe T. J. J. (2004a) Structure of the solar system’s dust disk: influence of massive bodies. In *Debris Disks and the Formation of Planets: A Symposium in Memory of Fred Gillett*, ASP Conf. Ser. Vol. 324 (L. Caroff, L. J. Moon, D. Backman, and E. Praton, eds.), pp. 143–144. Astron. Soc. Pacific Press, San Francisco.

Dermott S. F., Telesco C., Kehoe T., Kolokolova L., Mahoney-Hopping L., Novotny S., Wyatt M., and Zolensky M. (2004b) The origin and dynamics of interplanetary dust particles with application to the solar system dust bands and the structure of the Beta Pictoris debris disk (abstract # 01.06). *Bull. Am. Astron. Soc.*, 36.

Fisher R. S., Telesco C. M., Wyatt M. C., Dermott S. F., Kehoe T. J., Novotny S., Marinas N., Radomski J. T., Packham C., De Buizer J., and Hayward T. L. (2004) Mid-IR imaging

- of Beta Pictoris: the role of planetesimal collisions in the central disk (abstract # 174.05). *205th Annual Meeting of the American Astronomical Society Meeting*.
- Grogan K. and Dermott S. F. (2002) The size-frequency distribution of zodiacal dust band material. In *Dust in the Solar System and Other Planetary Systems*, COSPAR Colloquia Ser. Vol. 15 (S. F. Green, I. P. Williams, J. A. M. McDonnell, and N. McBride, eds.), pp. 136–139. Pergamon, Oxford.
- Grogan K., Dermott S. F., and Kehoe T. J. J. (2004) The distribution of asteroidal dust in the inner solar system. In *Planetary Systems in the Universe: Observation, Formation and Evolution*, Proc. IAU Symp. 202 (A. Penny, P. Artymowicz, A. M. Lagrange, and S. Russell, eds.), pp. 184–186. Astron. Soc. Pacific Press, San Francisco.
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- Mahoney-Hopping L., Dermott S., Kehoe T., Kolokolova L., and Grogan K. (2003) Sources of the solar system dust bands and interplanetary dust particles (abstract # 36.05). *Bull. Am. Astron. Soc.*, 35.
- Mahoney-Hopping L., Dermott S., and Kehoe T. (2004) Recent catastrophic disruptions of main-belt asteroids as a source of the solar system dust bands and interplanetary dust particles (abstract # 32.25). *Bull. Am. Astron. Soc.*, 36.

## Presentations

- Debris Disks and the Formation of Planets: A Symposium in Memory of Fred Gillett, Tucson, April 11–13, 2002. Talk by S. Dermott and T. Kehoe entitled “What can our solar system tell us about other circumstellar disks?”
- Asteroids, Comets, Meteors (ACM 2002), Berlin, July 29–August 2, 2002. Talk by S. Dermott entitled “Recent rubble-pile origins of the asteroidal solar system dust bands.”

- EGS-AGU-EUG Joint Assembly, Nice, April 6–11, 2003. **Invited talk** by S. Dermott entitled “Asteroidal IDPs may originate from Veritas and Karin.”
- 35th Annual Meeting of the American Astronomical Society Division for Planetary Sciences, Monterey, September 2–6, 2003. Poster paper by L. Mahoney-Hopping entitled “Sources of the solar system dust bands and interplanetary dust particles.”
- 35th Annual Meeting of the American Astronomical Society Division on Dynamical Astronomy, Cannes, April 20–23, 2004. Talk by S. Dermott entitled “The origin and dynamics of interplanetary dust particles with application to the solar system dust bands and the structure of the Beta Pictoris debris disk.”
- 2nd TPF/Darwin International Conference: Dust Disks and the Formation, Evolution and Detection of Habitable Planets, San Diego, July 26–29, 2004. Poster paper by T. Kehoe entitled “Collisional disruption of planetesimals in the  $\beta$  Pictoris debris disk.”
- 36th Annual Meeting of the American Astronomical Society Division for Planetary Sciences, Louisville, November 8–12, 2004. Poster paper by L. Mahoney-Hopping entitled “Recent catastrophic disruptions of main-belt asteroids as a source of the solar system dust bands and interplanetary dust particles.”

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